

# Cepheids, supernovae and the value of $H_0$

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**Abstract.** The calibration of the Type Ia supernova distances using HST observations of Cepheid variables is discussed. A new maximum likelihood method of calibration is applied to derive the PL relation for a composite sample of Cepheids in the LMC and in the SNIa host galaxies NGC5253 and IC4182. Our results show that the calibration of the Cepheid PL relation is robust both to sampling error and to luminosity and period selection effects. Hence, the outstanding uncertainty in deriving estimates of  $H_0$  from SNIa remains the dispersion of the SNIa luminosity function, and not unresolved systematic errors in its Cepheid calibration.

## 1. Introduction

Type Ia supernovae (henceforth SNIa) have long been regarded as useful cosmological distance indicators because they are observable to large velocity distances and their luminosity at maximum light displays a small intrinsic dispersion. In e.g. Sandage & Tammann (1993) the Hubble diagram of 34 SNIa in or beyond the Virgo cluster was found to have an observed V band dispersion of  $\sigma(M_v) = 0.36$  mag. Moreover, the linearity of the Hubble diagram indicated that these SNIa were not significantly affected by peculiar motions (after correction for Virgo infall) or luminosity selection effects. The mean absolute magnitude of these SNIa was found to be  $\bar{M}_v(\text{max}) = -19.47 + 5 \log(H_0/50)$ . In order to estimate  $H_0$  one must therefore determine independently the distance to one or more SNIa host galaxy.

HST has measured distances to IC4182 (host of SN1937C) and NGC5253 (host of SN1895B and SN1972E) from observations of Cepheid variables. These data yielded  $H_0 = 52 \pm 9$ , from SN1937C alone (Saha et al. 1994) and  $H_0 = 54 \pm 8$ , from the average of the three SNIa (Saha et al. 1995). In each case the SNIa were assumed to lie at the mean of the luminosity function. More recently Riess, Press & Kirshner (1995) have used the shape of the light curve to better constrain the luminosity at maximum light of SN1972E (the only one of the three SNIa with sufficient quality photometry to apply their method) and find evidence that SN1972E was significantly overluminous – yielding  $H_0 = 67 \pm 8$ .

In each of these analyses the Cepheid distances were determined assuming a distance modulus of  $\mu = 18.5$  for the LMC and fixing the slope of the PL relation in V and I to that obtained from a fiducial sample of LMC Cepheids (Madore & Freedman 1991). This was partly an attempt to avoid *Malmquist bias* – i.e. a systematic error in the distance determinations due to V-band luminosity selection effects in each HST-observed galaxy (HOG), for which there appeared to be some evidence (Saha et al. 1994). Nevertheless, adopting the LMC slope left the results susceptible to two further (possibly systematic) uncertainties: sampling error due to the finite size and different period range of the LMC and HOG Cepheids; and a possible intrinsic difference in PL slope due to e.g. metallicity effects (c.f. Chiosi, Wood & Capitanio 1993). Although allowance has been made for these sources of uncertainty in the error budget for the published  $H_0$  estimates, our aim in this work is to *explicitly* address their impact on  $H_0$  by fitting PL relations to a composite sample of Cepheids in *both* the LMC and each HOG.

## 2. Method

Our method of calibration is essentially the same as that developed to calibrate the Tully-Fisher relation for spiral galaxies in clusters (c.f. Hendry et al. 1996, and references therein), where the issues of sampling error and luminosity selection are generally of greater concern. Full details of the method applied to Cepheids will be presented in Hendry & Kanbur (1996, in preparation) and we merely summarise the principal points here. We assume an intrinsic absolute magnitude–log period relation which is linear and with absolute magnitude residuals which are Gaussian with mean zero and dispersion independent of period. We then determine the conditional distribution of absolute magnitude, given log period, in V for *observable* Cepheids after imposing a sharp V-band apparent magnitude limit. We next use this conditional distribution to form a conditional likelihood function for the apparent magnitudes and periods observed in the LMC and the HOG, introducing their relative distance modulus,  $\Delta\mu$ , as an additional unknown parameter. We then obtain maximum likelihood estimates of the slope and zero point of the composite PL relation, and of  $\Delta\mu$ .

We applied this calibration method using mean magnitudes and periods for the Cepheids in IC4182 and NGC5253 as published in Saha et al. (1994, 1995). For the LMC we used ‘raw’ magnitudes and periods from Madore (1985, Table I) which was the main source of the calibrating sample used in Madore & Freedman (1991). We corrected all magnitudes for galactic (foreground) extinction using B-band values from the Lyon Extragalactic Database (converting to V band following Pierce & Tully 1992). We corrected the LMC Cepheids individually for internal extinction based on reddening values tabulated in Martin, Warren & Feast (1979). Since Saha et al. (1994, 1995) find no evidence for significant internal extinction in either NGC5253 or IC4182 we applied no correction for internal extinction in either galaxy. We assumed a true distance modulus of  $18.5 \pm 0.1$  for the LMC, following Madore & Freedman (1991).

### 3. Results and discussion

Tables (1) and (2) list examples of the maximum likelihood estimates obtained for the apparent V-band distance modulus,  $\mu$ , of IC4182 and NGC5253 respectively, for a set of different selected period ranges, indicated by the lower and upper limits on  $\log P$  (in days) as given in column (2). In column (3),  $N_{\text{tot}}$  denotes the total number of Cepheids in each composite sample. In all cases a V band selection limit at  $V = 25$  was applied. The error on the estimated distance modulus was determined from Monte Carlo simulations.

The first example calibration uses essentially the same LMC stars as are plotted in Figure (4) of Madore & Freedman (1991), plus all the HOG Cepheids which are brighter than the magnitude limit; in the second example we instead restrict the fit to only the period range common to both samples. The third calibration is an example of the opposite extreme – where the sampled period ranges in the LMC and HOG have *no* overlap. The fourth calibration uses the full observable period range in the HOGs and extends the LMC period range down to  $\sim 1.5$  days, which is the range used in the fitted relations published in Madore & Freedman (1991) although the shorter period Cepheids are not plotted in their Figure (4).

We see from the Tables that the estimated distance moduli are robust to the selected period range, even when the ranges in the LMC and HOG are disjoint (although of course the uncertainty on  $\mu(V)$  is considerably larger in this case – particularly for NGC5253) and the quoted error bands for  $\mu(V)$  overlap. It seems clear, therefore, that sampling error and any intrinsic differential in slope of the PL relation do not significantly change the estimated distance modulus to either galaxy. Moreover, since our results are in excellent agreement with those of Saha et al. (1994, 1995), this confirms that the systematic effects of sampling error and luminosity selection in the SNIa host galaxies are small – thus vindicating the distance determinations of Saha et al. (1994, 1995).

Table 1. IC4182 apparent distance moduli: composite fits

	log period ranges	$N_{\text{tot}}$	$\mu(V)$
1.	LMC: 0.9 - 1.8		
	HOG: 0.4 - 1.4	45	$28.34 \pm 0.10$
2.	LMC: 0.9 - 1.4		
	HOG: 0.9 - 1.4	22	$28.25 \pm 0.12$
3.	LMC: 1.4 - 1.8		
	HOG: 0.4 - 1.4	32	$28.45 \pm 0.18$
4.	LMC: 0.2 - 1.8		
	HOG: 0.4 - 1.4	60	$28.43 \pm 0.08$

Figure (1) shows the derived intrinsic linear absolute magnitude–log period relation in V, corrected for luminosity selection, inferred from the composite samples of LMC + IC4182 (solid line) and LMC + NGC5253 (dotted line), using the fourth (and largest) calibration of Tables (1) and (2). LMC Cepheids are plotted as crosses, IC4182 Cepheids as open triangles and NGC5253 Cepheids as open squares. We can see from this figure that the two composite calibrations are almost completely indistinguishable, further indicating that we have successfully

Table 2. NGC5253 apparent distance moduli: composite fits

	log period ranges	$N_{\text{tot}}$	$\mu(V)$
1.	LMC: 0.9 - 1.8		
	HOG: 0.4 - 1.4	36	$28.02 \pm 0.12$
2.	LMC: 0.9 - 1.4		
	HOG: 0.9 - 1.4	19	$27.99 \pm 0.10$
3.	LMC: 1.4 - 1.8		
	HOG: 0.4 - 1.4	23	$27.97 \pm 0.28$
4.	LMC: 0.2 - 1.8		
	HOG: 0.4 - 1.4	51	$28.16 \pm 0.10$

Figure 1. Intrinsic PL relations for composite samples (see text)

corrected for any Malmquist bias and confirming that residual sampling errors are small.

#### 4. Conclusions: the value of $H_0$

Using the Cepheid apparent distance moduli deduced from the fourth example calibration – i.e.  $\mu(V) = 28.43 \pm 0.08$  to IC4182 and  $\mu(V) = 28.16 \pm 0.10$  to NGC5253 – and assuming both SNIa to lie at the peak of the luminosity function we estimate  $H_0 = 50 \pm 9$  from SN1937C and  $H_0 = 56 \pm 11$  from SN1972E. The error estimate on  $H_0$  is calculated by adding in quadrature the uncertainties on the Cepheid distance modulus and the SNIa apparent magnitude, and a further (conservative!) uncertainty of 0.15 mag. to allow for differential extinction between the Cepheids and SNIa in each HOG (see Saha et al. 1994). Note that in Saha et al. (1995) a value of  $H_0 = 58 \pm 9$  was obtained from SN1972E alone. Thus we find that our estimates of  $H_0$  are very slightly reduced – which ostensibly appears to be consistent with the general trend that luminosity selection effects tend to positively bias estimates of  $H_0$ . It is interesting to note, however, that if we adopt instead the distance moduli estimated by the second (smaller) calibration, using the same range of periods in the LMC and HOG, then our estimates for  $H_0$  are 54 (IC4182) and 60 (NGC5253), which are both larger than the Saha et al. values. This comparison demonstrates that sampling error can have just as large an effect as selection bias on the value of  $H_0$ , causing it to be erroneously decreased *or* increased, although the important point of our results is that *both* effects are shown to be very small here.

If we apply the LCS correction of Riess et al. (1995) to SN1972E we instead find  $H_0 = 65 \pm 8$ , which is also still in excellent agreement with the value deduced from the Cepheid distance to M96 (Tanvir et al. 1995) and the SN type II method of Schmidt et al. (1994) which completely by-passes the Cepheid distance scale.

Our analysis confirms that the Cepheid distances derived to these two SNIa host galaxies appear secure (at least provided that the LMC distance is secure) and accounting for possible sampling error and V-band luminosity selection does not significantly change the derived distance moduli. The outstanding uncertainty in estimating  $H_0$  with SNIa is therefore the dispersion in the SNIa lumi-

osity function at maximum light; this fact underlines the difficulty in making reliable statistical conclusions from only 2 or 3 data points. The LCS method offers one solution to this problem by reducing the dispersion, although the validity of luminosity–LCS correlations has recently been questioned in Tammann & Sandage (1995). Clearly measuring more distances to SNIa host galaxies would be a better solution. Indeed, since this conference took place distances to three more SNIa have appeared in preprints, and the issue of whether SNIa support a long or short distance scale should soon be resolved. Whatever the outcome, we conclude that the reliability of Cepheid distances in determining the SNIa zero point is not in doubt.

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